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Copper flows in buildings, infrastructure and mobiles: a dynamic model and its application to Switzerland

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Abstract During the last century, the consumption of materials for human needs increased by several orders of magnitude, even for non-renewable materials such as metals. Some data on annual consumption (input) and recycling/waste (output) can often be found in the federal statistics, but a clear picture of the main flows is missing. A dynamic material flow model is developed for the example of copper in Switzerland in order to simulate the relevant copper flows and stocks over the last 150 years. The model is calibrated using data from statistical and published sources as well as from interviews and measurements. A simulation of the current state (2000) is compared with data from other studies. The results show that Swiss consumption and losses are both high, at a level of about 8 and 2 kg/(cap year), respectively, or about three times higher than the world average. The model gives an understanding of the flows and stocks and their interdependencies as a function of time. This is crucial for materials whose consumption dynamics are characterised by long lifetimes and hence for relating the current output to the input of the whole past. The model allows a comprehensive discussion of possible measures to reduce resource use and losses to the environment. While increasing the recycling reduces losses to landfill, only copper substitution can reduce the different losses to the environment, although with a time delay of the order of a lifetime.

Keywords Dynamic material flow analysis · Copper flows · Buildings · Infrastructure · Mobiles · Stock-driven

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Introduction

Copper was very important for the evolution of human culture. It was probably the first metal used by man, primarily for its mechanical and aesthetic properties, to make tools and implements such as buckets. Then, the introduction of electricity at the end of the nineteenth century led to its use as an electrical conductor to transfer energy and information. Today, it is used in the building industry, thanks to its corrosion resistance, and in the cooling/heating-equipment industry due to its good heat conductivity. Copper is also processed worldwide in agricultural fertiliser and pesticides (fungicides) for its toxic effects on microorganisms.

This variety of applications and the very low price of the raw material explain the worldwide rise in copper demand in recent decades. Estimates carried out by Zeltner et al. (1999) van der Voet et al. (2000) and others (see references) show the following picture: (1) annual copper consumption worldwide was about 3 kg per person and year for 1990, (2) 70% of that amount is newly mined copper and only about 30% is recycled, (3) worldwide mineable copper stocks are estimated to be about 2300 million tons. Only about 500 million tons of these are considered to be economically mineable with current technology. The value of 3 kg per person and year is a result of the data compilation in Jolly and Edelstein (1989) and Metallgesellschaft (1992) for many different countries as well as the whole world. Zeltner et al. (1999) presented a summary of the results. In 1990, according to those references, the world population was 5300 million people and about 15,200 tons of copper was used in manufacturing industries.

The 500 million tons of economically mineable copper has to be compared with the worldwide annual consumption of newly mined copper, which was more than 10 million tons in 1990 (see above). This predicted shortage in natural copper resources is one reason to change to 'more sustainable' copper management. This means using non-renewable material in a way that minimises consumption losses as far as possible in order to ensure its continued long-term use. Other reasons include the environmental impacts of mining primary resources such as high water and energy use, large amounts of tailings and slag.

Besides this potential resource scarcity and the environmental impact of mining, copper use has also led to ecological and ecotoxic problems. Indeed, copper contained in fertilisers and fungicides and its use in buildings (roofs) has led to its diffuse distribution into the environment, namely into soils and aquatic systems (Xue et al. 1996; Sigg et al. 1999; Chèvre et al. 2010).

Both the resource and environmental aspects have led to numerous studies. They range from regional copper studies on a large scale down to microscopic-effect studies on microorganisms on the micro scale. These studies are important for understanding all aspects of copper use. In this study, we focus on the large-scale aspects.

Numerous copper flow analyses have been performed to describe the present copper flows for continents, nations, regions and cities: For the USA: Tarr and Ayres (1990) and Zeltner et al. (1999); Europe: Spatari et al. (2002),; Germany: Erdmann et al. (2002); Holland: van der Voet et al. (2000); Sweden: Bergbäck (1992), Iverfeldt (2001), Sörme (2003) and Hedbrant (2003); Switzerland: Baccini et al. (1993), von Arx (1998) and Wittmer et al. (2003); China: Wang et al. (2008).

Copper flow analyses in the context of historical developments during the twentieth century have been carried out for Sweden by Bergbäck et al. (1994).

Zeltner et al. (1999) developed a mathematical model to dynamically simulate the copper cycle for the USA between 1900 and 2100. It included the long residence times of copper. Similar studies have been carried out for New Zealand by Johnstone (2001a, b), for the USA by Spatari et al. (2005) and for Japan by Daigo et al. (2009).

The aim of this study is to present and apply a new approach to describe the copper flows in buildings, infrastructure and mobiles. The model is a further development of that set up in Zeltner et al. (1999) on the basis of a mathematical material flow analysis (MMFA).

The crucial questions to be answered are:

(1) How did the copper flows and stocks develop in the past up to the present level? In particular, which stocks have accumulated on the consumption side and in the environment and which are flows of residues to the environment?
(2) Which key parameters describe the copper cycle to a good approximation?
(3) How could 'more sustainable' copper management be reached in terms of resource and waste disposal aspects as well as losses to the environment?

Method

The method used is MMFA. By this, we mean the combination of conventional material flow analysis (MFA) with state-of-the-art mathematical modelling concepts. The MFA method was introduced and applied to specific regions in the mid-1980s by Baccini and Brunner (1991). It was extended to the MMFA by Baccini and Bader (1996), who described it in detail. In the past 10 years it has been applied in many studies within different fields: flows relating to buildings and infrastructures: Zeltner et al. (1999), Sörme (2003), Hedbrant (2003), Johnstone (2001a, b), Kohler et al. (1999), Müller et al. (2004); substance and energy flows induced by the implementation of large-scale energy systems: Bader et al. (2003), Hug et al. (2004); goods, metal and nutrient flows in the anthroposphere: van der Voet et al. (2000), Pfister et al. (2005), Binder et al. (2001), Schmid Neset et al. (2006, 2008) and others as well as ongoing work. Recently, the method has been extended to include the dynamic financial flows of investments, interest and return payments in Bader et al. (2006). The procedure is as follows: (1) system analysis, (2) mathematical model, (3) calibration of the model and (4) simulations, including sensitivity, uncertainty analysis and scenario calculations.

System analysis

The system analysis defines the system border and the approximation level (balance volumes and flows) appropriate to the questions addressed.

The system border is the geographical border of Switzerland and the time period considered is 1840–2060. The long time period is important, since copper has long residence times of up to 50 years and more in buildings and infrastructures. The system is a Swiss adaptation and generalisation of the one designed for the USA by Zeltner et al. (1999).

The key balance volumes are buildings, infrastructures and mobiles. They provide services to various human activities. The copper supply for buildings, infrastructure and mobiles comes from imports (trade) and domestic production. Whenever copper is used, emissions to soil and aquatic systems occur from abrasion and corrosion. When copper is no longer used in buildings, infrastructures and mobiles, it is directly recycled, recycled via dismantling or disposed of to landfill. The system is shown in Fig. 1.

The differences to the system in Zeltner et al. (1999) are the following:

(i) There has been no copper mining and ore processing in Switzerland since 1900.
(ii) The various copper imports and exports had to be distinguished since the individual flows are of interest and data for domestic flows only were not available from the statistics.
(iii) The abrasion and corrosion flows from roofs, cars etc. to the soil and aquatic compartments are taken into account.

The system of Fig. 1 consists of eight balance volumes (boxes), three sub-balance volumes and 32 flows (arrows), making a total of 43 variables. Their meaning is described in the following section.

Balance volumes

Trade: Represents all traders who import semi-products, scrap and copper-containing products, which are sold to various 'consumers' and foreign countries (export).

Domestic production: Processing of semi-products, raw copper, scrap, keys, watchcases, balls from ball-point pens etc.

Buildings, infrastructures and mobiles: Storage and use of copper products.

Copper in buildings: Cables and wires for electricity and telecommunications, heating and plumbing (pipes) and roof (sheets, gutters, cladding of dormer windows).

Copper in infrastructures: Cables and wires of power supply and telecommunication systems, over-ground cables for railway, trolleybus and tramway systems.

Copper in mobiles: Locomotive engines, cars, trucks, electric and electronic equipment (cookers, refrigerators, vacuum cleaners, hi-fi units, computers…) and other equipment (tools, instruments, decorations, keys, screws …).

Dismantling and demolition: Processing of copper from buildings and infrastructures.

Soil and aquatic compartment: accumulation of copper from abrasion and corrosion. The transport, percolation and leachate in these compartments are not considered here.

Landfill: sink for copper as residues from dismantling/ demolition, mobiles and the domestic production industry.

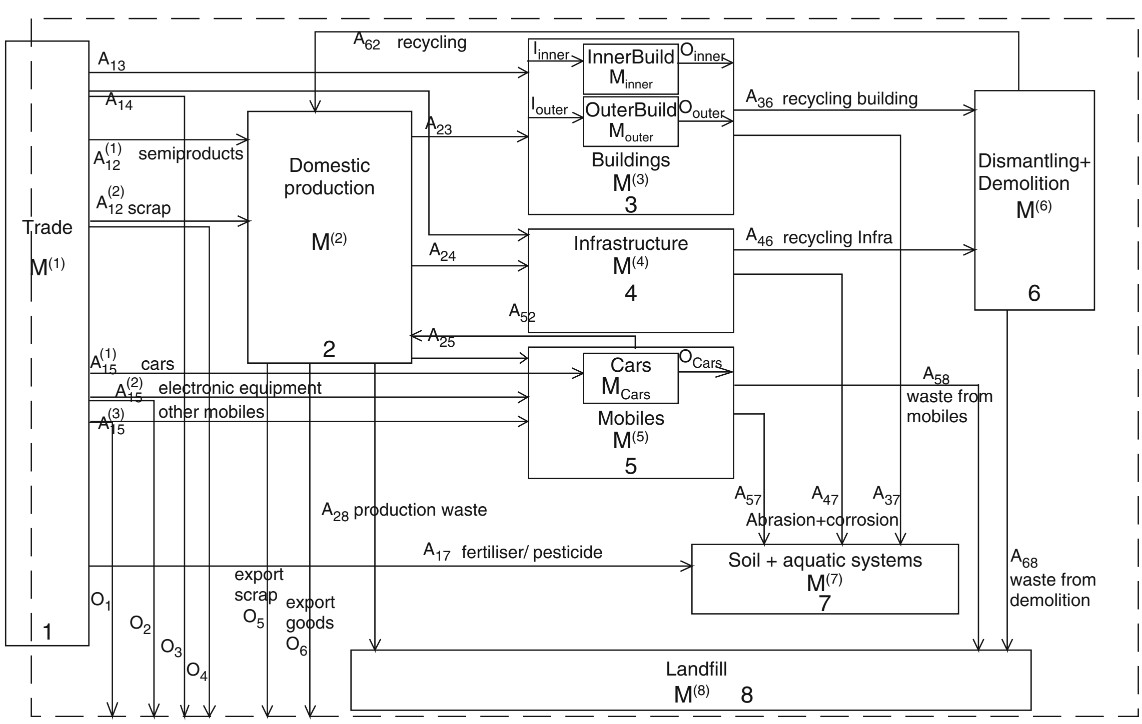


Fig. 1 Swiss copper cycle system

The stocks of the balance volumes are described by the variables $M^{(1)}, \ldots, M^{(8)}$.

Sub-balance volumes Cars: Storage and use of cars (important copper 'consumers'). This is a sub-balance volume of mobiles.

InnerBuild: Storage and use of copper within buildings (cables and wires for electricity and telecommunication, heating and plumbing (pipes)).

OuterBuild: Storage and use of copper in building envelopes (sheets, gutters, cladding of dormer windows).

Flows

Output flows of trade:

A_{13}: Copper in imported long-term products to buildings (cables, wires, pipes, raw armatures)
A_{14}: Copper in imported long-term products to infrastructures (cables, wires, overhead lines)
O_3: Copper in exported long-term products (cables, wires, pipes)
$A_{12}^{(1)}$: Copper in imported semi-products and as raw material to the domestic production industry (metal sheets, metal bands, copper bars,…)
$A_{12}^{(2)}$: Imported copper scrap to the domestic production industry
O_4: Exported copper scraps
$A_{15}^{(1)}$: Copper in imported cars
$A_{15}^{(2)}$, O_2: Copper in imported/exported electric and electronic equipment (mobiles without cables and wires)
$A_{15}^{(3)}$, O_1: Copper in imported/exported other mobiles
A_{17} Copper in imported fertilisers/pesticides

Output flows of domestic copper production

A_{23}: Copper in domestically produced sheets, gutters, cables, wires and raw armatures
A_{24}: Copper in domestically produced cables, wires
A_{25}: Copper in domestically produced electric, electronic and other goods (keys, watchcases, balls from ball-point pens)
O_5, O_6: Export of copper in scrap and goods from domestic production
A_{28}: Copper in production waste (slag)

Output flows from buildings, infrastructures and mobiles

A_{36}, A_{37}: Copper in dismantled long-term products
A_{52}: Copper in separately collected old mobiles
A_{58}: Copper in waste from mobiles

Output flows from 'cars':

O_{Car}: Copper in old cars. This flow is part of the output flows A_{58}, A_{52}

Input and output flows from InnerBuild and OuterBuild:

I_{Inner}, O_{Inner}: Copper in input and output of InnerBuild (cables, wires, pipes, raw armatures)
I_{Outer}, O_{Outer}: Copper in input and output of OuterBuild (sheets, gutters, cladding of dormer windows)
A_{37}, A_{47}, A_{57}: Copper in abrasion and corrosion from buildings, infrastructures and mobiles

Output flows from dismantling/demolition

A_{62}: Copper in dismantled goods which can be reused in the domestic production industry or exported
A_{62}: Copper in waste from dismantling/demolition

Mathematical model

The model equations describe the present knowledge about the system in mathematical terms.

The system knowledge was gained, similarly to Zeltner et al. (1999), during extended urban exploration studies of the Swiss copper cycle in the twentieth century (Wittmer 2006; Lichtensteiger 2006).

The key balance volumes 'Buildings, Infrastructures and Mobiles' represent the core of the system. They are described as follows:

(i) The copper stocks as a function of time are given by parameter functions representing the stock per person.
(ii) The residence time distribution, also called the transfer function, defines the amount of copper input into a stock at a time t_{Ip} which leaves the stock (after its lifetime) at a time t_{Op}.
(iii) The distribution pattern of the used copper to recycling, landfill and the environment is described by a time-dependent transfer coefficient representing the 'disposal decision' of the owners of the buildings, infrastructure and mobiles.
(iv) The fraction of imported copper in the copper input is given.

This is a 'stock-driven' model approach. It is the most appropriate description for the durables (lifespan of years) in these three stocks. The reason is as follows: the function of durables is to provide utility or access to people without being consumed. A certain *amount* of durables (the stock) is needed to guarantee the desired utility. Using copper instead of other materials reflects the stakeholders' intention to use material of high and durable quality. The input, representing stock increase and replacement, then follows according to the lifespan of the durables.

The contrast to a 'stock-driven' approach is an 'input-driven' approach. This is appropriate to describe consumables such as food, cosmetics etc. which are characterised by a short lifespan (days, weeks). Consumers use a certain amount of such expendable goods per unit of time, i.e. a certain input. The goods are simultaneously consumed while providing the 'service'.

The three balance volumes without stocks, namely trade, domestic production and dismantling/demolition are described by import/export ratios, amounts of imported and exported goods as well as scrap and process qualities such as recycling and waste coefficients. The import/export ratio, which can be time dependent, reflects the way in which the traders act: they must cover domestic demand while also selling copper abroad. Finally, the two environmental compartments of soil + aquatic and landfill are copper sinks. The corresponding flows are residual flows from supply, consumption, waste management and fertiliser/pesticide use, respectively. The residual flows from consumption are proportional to the amount of copper exposed to abrasion/corrosion and the fertiliser flows are simulated according to fertiliser statistics. The 'stock-driven' approach taken here contrasts to that of previous studies (Zeltner et al. 1999; Johnstone 2001a, b; Spatari et al. 2005; Daigo et al. 2009). Zeltner et al. (1999) applied an input-driven approach because relatively good input data were available at that time compared with very little data for US stocks. This made it impossible to calibrate a stock-driven model. The same approach was applied by Spatari et al. (2005) using a more detailed database and a different residence time distribution. A similar study was recently carried out for Japan by Daigo et al. (2009). The cohort approach of Johnstone (2001a, b) is mathematically equivalent to the input–output approach of Zeltner et al. (1999). Müller et al. (2004) applied a stock-driven approach to describe the timber cycle in buildings.

The mathematical equations of the stock-driven approach used here are described for buildings in the Appendix. For a more detailed description of all the equations, see Wittmer (2006).

The 29 parameter functions of the model: a_{Build}, … are the characteristic quantities describing the system behaviour in this approach. They are determined according to the two driving forces of the system, namely:

(a) Technical limitations or environmental conditions: the abrasion/corrosion rates a_{Build}, a_{Infra}, and a_{Mobi}, and the processing parameters (fraction of waste in recycling and scrap flows to production) $k_{\mathrm{Rec\text{-}Waste}}$ and $k_{\mathrm{Scrap\text{-}Waste}}$.

(b) Stakeholders' decisions:
The stocks: P_{Inner}, P_{Outer}, P_{Infra}, P_{Mobi} and P_{Cars}, the fractions of imported to domestically produced copper: $k_{\mathrm{Imp\text{-}Build}}$, $k_{\mathrm{Imp\text{-}Infra}}$, $k^{(1)}_{\mathrm{Imp\text{-}Mobi}}$, $k^{(2)}_{\mathrm{Imp\text{-}Infra}}$, the import/export ratios of the trade: $k^{(1)}_{\mathrm{Imp\text{-}Exp}}$, …, $k^{(4)}_{\mathrm{Imp\text{-}Exp}}$ and the amount of imported scrap and exported goods: $P_{\mathrm{Imp\text{-}Scrap}}$ and $k_{\mathrm{Imp\text{-}Scrap}}$.

The remaining eight parameter functions, namely the lifetime distributions k_{Inner}, k_{Outer}, k_{Infra}, k_{Mobi} and k_{Car} and the deposition/recycling function $k_{\mathrm{Mobi\text{-}Waste}}$ and k_{Rec} as well as the fertiliser P_{Fert} used are determined by both the technical limitations/environmental conditions and the decisions of the stakeholders.

The system of equations described in Appendix A1 was implemented in the SIMBOX computer program (Baccini and Bader 1996). The equations were solved numerically using the Newton–Raphson iteration procedure with automatic adaptation of time steps to the specified convergence threshold. All calculations were performed on a Pentium IV PC (2400 MHz).

Calibration and 'business as usual 2000' scenario

As already mentioned in the "System analysis" section, the period considered is 1840–2060. However, calibration is only possible for the past, i.e. for 1840–2000. For the period, 2000–2060 assumptions have to be made for the parameters.

We extrapolate the past data in a conservative, moderate way to the future, henceforth referred to as the 'business as usual 2000' or reference scenario. This means that most of the future parameters are kept constant at the level of the year 2000. A small improvement is assumed only for recycling of waste from mobiles and a conservatively low growth with saturation for the various stocks. So the reference scenario assumes no technological jumps, large growth or changes in habits. We should point out that this scenario is not a prognosis of the future. It just shows what would happen when we extrapolate the 'business as usual' of the year 2000. In this sense it should be considered as a 'reference scenario'. If the twentieth century growth pattern were to continue, the flows and stocks would exceed those of the 'reference scenario'. If substitutes were to replace copper, and recycling/emissions improved, the flows and stocks would be smaller.

Calibration is used to find appropriate parameter functions and fit them to the available data.

Data sources

Data including uncertainty for the various parameter functions are based on the following sources:

- Federal trade statistics (import–export statistics)
- Statistics and knowledge of transportation enterprises, electrical power utilities, telecommunication companies

and associations of various tradesmen such as plumbers, electricians and heating technicians
- Literature: Other studies, technical reports etc.
- Measurements: Field studies of individual selected buildings
- Interviews with experts of the production companies and tradesmen.

A detailed inventory of all stocks and flows was made using all available data. The whole database is quite large and is given in detail in Wittmer (2006) and Lichtensteiger (2006). The uncertainty of the data was estimated as follows (for details see Wittmer 2006):

(a) Uncertainty for stocks and lifetimes: the study of the inventory of the stocks has identified large number of items (about 240 for the building, 40 for infrastructure and 70 for mobiles). For each item the standard deviation (STDV) of the amount of copper was estimated based on the available data and on interviews with experts. The stock is just the sum over these items. Hence the STDV of the stock can be calculated using Gaussian error propagation. The results for the relative STDV were 15% for buildings, 23% for the infrastructure and 26% for mobiles. The differences are the result of the different numbers of items and different individual STDVs. The average lifetimes and widths of the lifetime distribution are the weighted average over the lifetimes and widths of the items. Similar is true for their STDV.
(b) Abrasion/corrosion coefficients, recycling/dismantling rates and import/export ratios at the trades: The STDV of those quantities was estimated based on the quality of the available data and on discussions with experts. The value for the relative STDV ranges from 5 to 100%. For instance, a transfer coefficient with values of 0.9 and 0.05 had relative STDV of 5 and 100%, respectively according to the current knowledge. All these data namely stock inventory, average lifetimes, import/export ratios of the trade, abrasion/corrosion coefficients and recycling/dismantling rates were used as an estimation for the parameter functions discussed in "Mathematical model" section above. The result was that the data were within a range of one standard deviation of the simulated flows and stocks. Appendix A2 of this article presents a summary of the data compiled in these two references and the calibration procedure for buildings.

Scenarios

The model in "Mathematical model" section can be used to simulate possible scenarios for the copper cycle. Starting from the reference scenario (Calibration and 'business as usual 2000' scenario), various strategies such as increasing lifetimes and/or recycling rates can be simulated by changing the corresponding parameters. However, some important scenarios require adaptation of the model, not only a change of parameter values. This adaptation will be discussed for the following two key scenarios.

Scenario: Copper ban in the envelope of buildings

This strategy has been under discussion for several years. The aim is to reduce abrasion/corrosion from roofs, gutters and drain pipes to receiving waters and soils. For the adaptation of the model equations, see Appendix A3. The equations would naturally also have to be changed in a similar way to take account of the copper ban for the interiors of buildings, infrastructures, mobiles and cars, with individual prohibition times.

Scenario: Copper ban + copper dismantling in the envelope of buildings

This scenario is an intensification of the previous one, since forced substitution is considered in addition to a copper ban for new and renovated buildings. For the adaptation of the model equations, see also Appendix A3. Approaches similar to those above could be applied to the *InnerBuild*, infrastructures, mobiles and cars if these were realistic scenarios.

Results and discussion

The key questions to be discussed in this study are: (see also "Introduction")

- What are the main flows with respect to resource use, waste disposal and residues to the environment?
- How did they grow as a function of time?
- Which stocks were accumulated on the consumption side and in the environment?
- What are the driving forces (key parameters) for reducing the use of resources and the flow of residues to the environment?
- What possible limiting factors could reduce the use of resources and the loads to the environment?

The discussion of these questions requires two additional variables dependent on those of "System analysis" section.

The separation efficiency $E(t)$:

$$E(t) = \frac{A_{62}(t) + A_{52}(t)}{A_{62}(t) + A_{68}(t) + A_{52}(t) + A_{58}(t)} \quad (1)$$

The consumption loss $U(t)$:

$$U(t) = A_{28}(t) + A_{58}(t) + A_{68}(t) + A_{57}(t) + A_{47}(t) + A_{37}(t) \qquad (2)$$

The separation efficiency is the fraction of recycling in the total waste from consumption and was discussed in more detail in Zeltner et al. (1999).

The consumption loss is the copper flow in all internal balance volumes to landfills and the soil/aquatic system.

Flows and stock for the year 2000

Figure 2 shows all flows and stocks for the year 2000. Table 1 presents input/output flows and stocks for the main balance volumes in the years 2000 and 2060.

The main characteristics of the copper cycle in the year 2000 are (Fig. 2): total consumption of about 8 kg/(cap year), total imports of 24 kg/(cap year), exports of 18 kg/(cap year), a net import of 5.5 kg/(cap year), a recycling volume of 4.2 kg/(cap year) and a loss of 1.8 kg/(cap year) to landfill and soil + aquatic systems. The stock in building + infrastructures + mobiles is 222 kg/cap. The calculated stock in landfills is 67 kg/cap, which is about a third of the stocks in building + infrastructures + mobiles. The residual flow to soil + aquatic environment is about 100 g/(cap year): 70 g/(cap year) originates from fertiliser/pesticides, 20 g/(cap year) from buildings, 6.5 g/(cap year) from infrastructures, and 3.4 g/(cap year) from mobiles. The 1.7 kg/(cap year) of copper disposed to landfill splits into 1.3 kg from mobiles, 370 g/(cap year) from infrastructure and buildings and 20 g/(cap year) from domestic production. The 'pure trade' and export flows are consequently much larger than the internal flows.

Swiss consumption is 2.8 times higher than the estimated worldwide consumption of about 3 kg/(cap year) but within the range of industrialised countries like Japan and USA with consumptions of 9.8 kg/(cap year), see Daigo et al. (2009), and 7.9 kg/(cap year), see Spatari et al. (2005).

The ratio of recycled to consumed copper is about 50%, which can be interpreted as the 'degree of regional supply' Wittmer (2006). The separation efficiency is only about 0.71, which is comparable to the highest estimated value for the USA given in Zeltner et al. (1999). This is due to the relatively low recycling coefficient of 0.4 for mobiles.

Comparison with other studies

The most careful and detailed database for copper stocks and flows was compiled for the Stockholm area by Lohm et al. (1997), Sörme (2003) and Hedbrandt (2003). Johnstone (2001a) gives a value for the copper stock of a

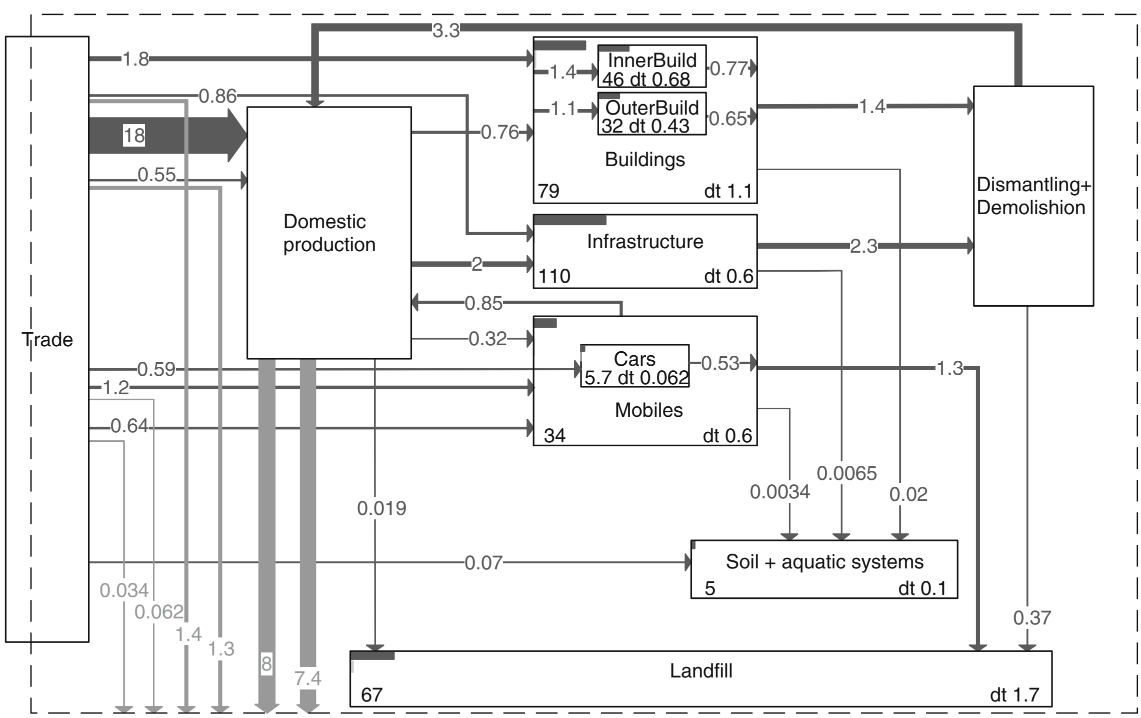


Fig. 2 Copper flows (kg/(cap year)) and stocks (kg/cap) for the year 2000. The width of the arrows is proportional to their value. Stocks are represented by the *upper rectangle* in the upper left corner and the corresponding number in the lower left corner of the boxes. The number in the lower right corner describes the stock change rates. The *inner/outer rectangles* express stock increases/decreases, respectively

Table 1 Stocks, input and output flows for key balance volumes in the years 2000 and 2060

	2000			2060		
	Stock (kg/cap)	Input (kg/(cap year))	Output (kg/(cap year))	Stock (g/cap)	Input (kg/(cap year))	Output (kg/(cap year))
Buildings	79	2.5	1.4	109	2.7	2.6
Infrastructures	110	2.9	2.3	120	2.9	2.9
Mobiles	34	2.7	2.1	49	3.4	3.4
Buildings + infrastructure + mobiles	222	8.2	5.8	280	9.1	8.9
Landfill	67	1.7	–	180	1.9	–

Table 2 Data for various stocks and flows from other studies

Stock infrastructure Stockholm	1995	97 kg/cap	Sörme (2003)
Stock buildings Stockholm	1995	49 kg/cap	Sörme (2003)
Stock cars Stockholm	1995	6.5 kg/cap	Sörme (2003)
Total stock in Stockholm	1995	175 kg/cap	Bergbäck et al. (2001)
Stock model house, New Zealand	1972	307 kg/House	Johnstone (2001a)
	1994	139 kg/House	
Input to buildings, infrastructures and mobiles, Stockholm	1995	3.3 kg/(cap year)	Sörme (2003)
Output of buildings, infrastructures and mobiles, Stockholm	1995	0.4 kg/(cap year)	Sörme (2003)
Input to buildings, infrastructures and mobiles, Sweden	1994	14.1 kg/(cap year)	Nilarp (1994)
Input to buildings, infrastructures and mobiles, Europe	1994	8 kg/(cap year)	Spatari et al. (2002)
Output of buildings, infrastructures and mobiles, Europe	1994	2 kg/(cap year)	Spatari et al. (2002)
Emissions of buildings, infrastructures and mobiles to soil and water, Stockholm	1995	17.4 g/(cap year)	Sörme (2003)
Emissions of buildings + infrastructure, Lausanne, Switzerland	1998–2008	11.5 g/(cap year)	Chèvre et al. (2010)
Life time of OuterBuild, New Zealand	1994	50 years	Johnstone (2001b)
Lifetime of InnerBuild, New Zealand	1994	40 years	Johnstone (2001a)
Runoff rate Stockholm	1995	1 g/(m^2 year)	He et al. (2001)

'model house' in New Zealand. Average input and output flows were estimated by Spatari et al. (2002) for Europe. Wittmer (2006) gives a literature overview for values of copper stocks of buildings.

Johnstone (2001b) reports on the lifetimes for OuterBuild and InnerBuild. He et al. (2001) estimate the runoff rates from copper roofs. Sörme and Lagerkvist (2002) and Sörme (2003) estimated the loss of buildings, infrastructure and mobiles to the aquatic environment by measuring the copper concentration in the inlet to wastewater treatment plant. Table 2 lists the data from these studies.

A comparison of Table 2 with the corresponding values of this study in Fig. 2 and Table 1 shows the following. The stocks, input flows and emissions agree quite well, taking into account the differences between the countries and the large uncertainties of the data (Sörme 2003). Only our output flow from buildings, infrastructures and mobiles is much larger than the estimate for Stockholm. However, this value of 0.4 kg/(cap year) seems too low compared to the corresponding input flow of 3.3 kg/(cap year) and the value of 2 kg/(cap year) of Spatari et al. (2002) for Europe. Note that the values reported by Johnstone (2001a) are per house and not per person.

Development of flows and stock as a function of time

The 'snapshot' for the year 2000 in Fig. 2 shows an overview of the current copper flows and stocks. However, it gives no insight into and understanding of how these flows and stocks have developed as a function of time.

Figure 3 shows that the growth of the consumption stocks in the twentieth century is different for buildings/mobiles and infrastructures. The data records showed that buildings and mobiles grew linearly up to 1920 and then changed to strong logistic growth. The reason is the electrification of households and the improvements in building technologies (roofs, gutters, installations) around 1920–1940. Infrastructures show a two-step logistic growth: the

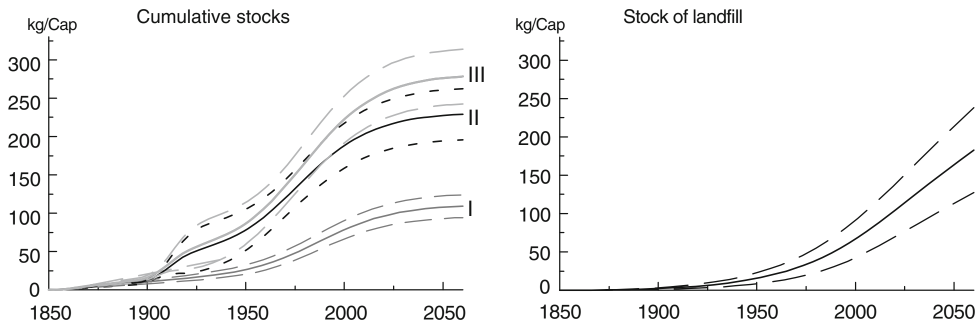


Fig. 3 Cumulative stocks (kg copper/cap): *I*: buildings $M^{(3)}$, *II*: buildings + infrastructures $M^{(3)} + M^{(4)}$, *III*: buildings + infrastructures + mobiles $M^{(3)} + M^{(4)} + M^{(5)}$. Stock of landfill $M^{(8)}$ (kg copper/cap). The *dashed lines* show the standard deviations

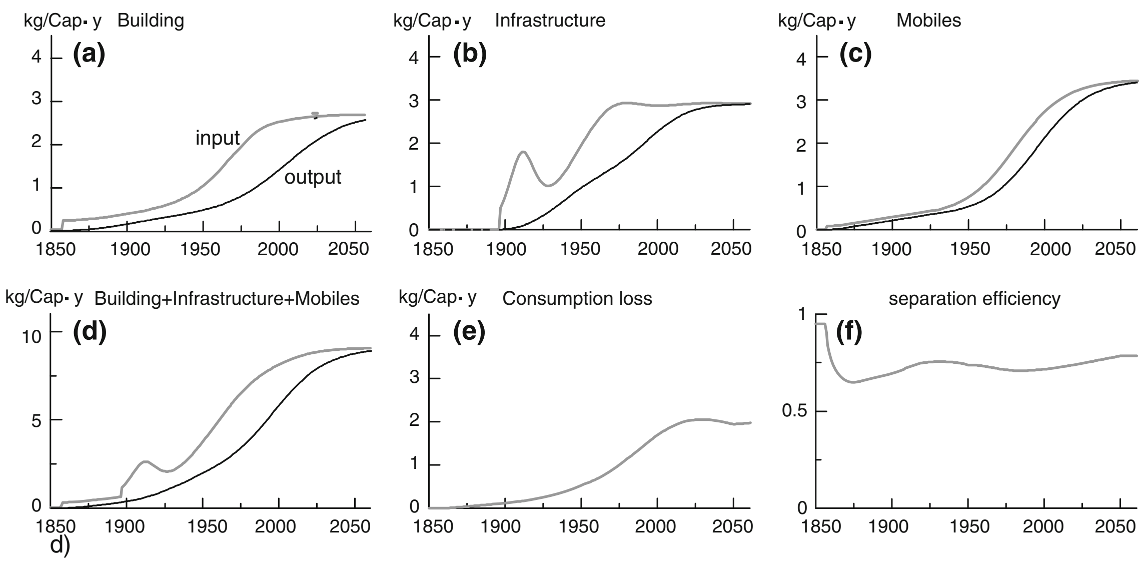


Fig. 4 Input and output flows (kg copper/cap and year) for **a** buildings, **b** infrastructures, **c** mobiles, **d** buildings + infrastructures + mobiles, **e** consumption loss and **f** separation efficiency. The upper curves show the input flows; the lower ones show the output flows

first step reflects the electrification age and the second one, with a growth rate peaking at about 1960/1990, a large growth of infrastructure (power stations, new grids and telecommunications systems).

Landfills grew exponentially up to 2000 and changed to a linear growth pattern after 2000 for the 'business as usual 2000' scenario. Clearly, for other scenarios, the landfills would either continue to grow exponentially (for continuing growth in stocks) or more slowly (with substitution of copper).

Induced by the growth of stocks, the input and output flows of buildings, infrastructures and mobiles and the consumption loss also show large growth in the twentieth century (Fig. 4). (The two peaks in infrastructure are due to the double logistic growth, see above.)

Due to the large residence time in buildings and infrastructures, the time delay between input and output flows is quite large. As a consequence, a large increase of the output, especially from buildings, is expected in the coming decades. This is important for planning dismantling capacities.

The consumption loss increases until 2000 to a high level of about 2 kg/(cap year). This high loss is due to the relatively small separation efficiency of about 70% (Fig. 4). Some 98% of this amount is deposited in landfills (without further measures[1]), and the rest is distributed diffusely to the soil and aquatic compartments through abrasion/corrosion/fertilisers.

Uncertainty and sensitivity analysis

A crucial question concerns the uncertainty of the simulated flows and stocks. The uncertainty of the input data was discussed in section calibration above. Using

[1] In Switzerland, separation of copper from the bottom ashes of municipal solid waste incineration is currently in preparation (Jordi 2004).

Gaussian error propagation, the standard deviation of the flows and stocks were calculated. Figure 3 shows the result for the stocks. The relative standard deviation for the stocks are about: 15% for buildings, 21% for buildings interior, 23% for buildings envelope, 25% for infrastructure, 27% for mobiles, 37% for landfills, 31% for the consumption loss to landfill and soil + aquatic, 26% for the import to buildings, infrastructure and mobiles and 39% for the loss to soil + aquatic system. Thus the relative STDVs are up to 40%. This uncertainty is about what can be expected from simulation from rather uncertain data. An important question is which input data uncertainty is most responsible for the uncertainty of those stocks and flows. An 'uncertainty related sensitivity' analysis (see Brun et al. 2001; Schaffner et al. 2009) shows the following: for all stocks the uncertainty of the stock saturation accounts for the largest part of the uncertainty. For the losses to soil + aquatic systems the uncertainty of the corrosion coefficients is responsible for more than 95% of its uncertainty followed by the above-mentioned uncertainties of the stock saturations.

Scenarios for reducing resource use and consumption loss

A sensitivity analysis shows that the four 'parameters' of residence time τ, separation efficiency E, 'level of copper usage' (stocks) and corrosion coefficients are the key drivers for reducing net imports, losses to soil + aquatic systems and losses to the landfills. Their qualitative effect is shown in Table 3.

According to this analysis, the following scenarios will be discussed.

Increase of τ: Between 2000 and 2025, τ is assumed to increase linearly from 40 to 60 year for buildings and infrastructures, and from 14 to 20 year for mobiles. This scenario induces a reduction of the input and the output flows (delayed) of the consumption.

Increase of separation efficiency E: E depends on the recycling rate of buildings and infrastructures and the disposal rate of mobiles. The former is assumed to be 0.9 (level of 2000). The latter is assumed to decrease linearly between 2000 and 2025 from 0.6 to 0.1. This scenario only affects the distribution pattern of the outputs of the consumption for recycling and disposal. There is no effect on input, output of consumption and recycling rate.

Decrease of stocks: The two scenarios 'copper ban' and 'copper ban + forced dismantling' introduced in "Scenarios" section are designed to decrease the 'level of copper usage' (stock) by substituting copper for other materials. A ban stops the input into consumption. As a consequence, the corresponding stock and output flows decrease slowly according to the lifetime. Forced dismantling alone, i.e. without an input ban, is not considered as a reasonable scenario. The effect would be similar to a decrease in lifetime. For the 'ban' scenario, a copper ban for the envelope of buildings after $t_{\mathrm{Ban}}^{(\mathrm{Outer})} = 2010$ (see Eq. 9a) was assumed. For the 'dismantling' scenario (forced dismantling), the following specific dismantling rate for the envelope of the building was assumed (see Eq. 10a):

$$P_{\mathrm{Outer}}^{(\mathrm{Dism})}(t) = \begin{cases} 0 & t \leq t_{\mathrm{Ban}}^{(\mathrm{Outer})} \\ 0.025 & t > t_{\mathrm{Ban}}^{(\mathrm{Outer})} \end{cases}$$

Since the average lifetime of the envelope is 40 years, this dismantling rate means roughly a doubling of the rate induced by a 'copper ban' alone.

Decrease of corrosion rate: This scenario would clearly reduce the losses to aquatic systems and soils. However, this measure is difficult to realise. It is known that copper–zinc alloys have smaller corrosion rates. But it seems impossible to cover all copper sheets, gutters etc. with corrosion-reducing films. Therefore, this scenario is not discussed.

Figure 5 shows the effect of the scenarios on the landfills, the consumption loss, the losses to soil + aquatic systems and the import to consumption. The first three quantities describe the residual flows to the environment, and the last one is an indicator of resource use. To understand the behaviour of these flows and the landfill stock as a function of time, it is necessary to keep in mind the different modes of action of the scenarios discussed above.

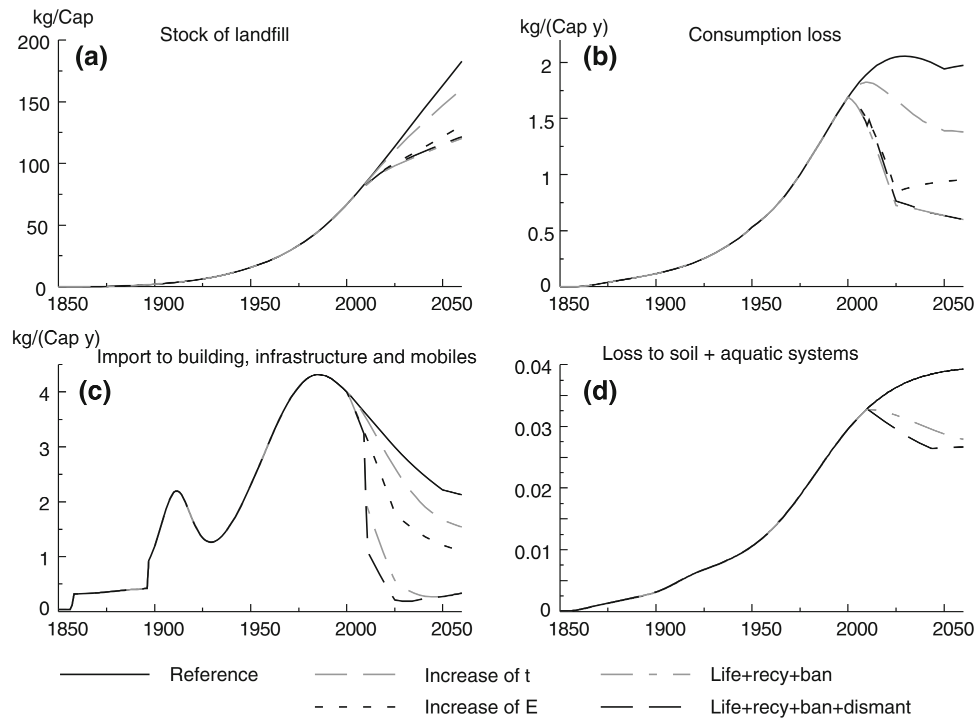
Table 3 Qualitative effect of the four key parameters on the three key flows

	Net import	Losses to soil + aquatic	Losses to landfills
Increase of τ	Reduction	No	Reduction
Increase of E	Reduction	No	Reduction
Decrease of stocks	Reduction	Reduction	Reduction
Corrosion rate	No	Reduction	No

Imports

As shown in Fig. 5, all scenarios reduce the import without any delay in time. Only the reasons are different. For an increased lifetime or a copper ban, the input to consumption is reduced and zero respectively. For increased separation efficiency or additional forced dismantling the recycling flows are increased. Reduced inputs and increased recycling flows both induce a reduction of import.

Fig. 5 Results of the first four scenarios: **a** the landfill stock (kg/cap), **b** consumption loss (kg/(cap year)), **c** import to buildings, infrastructures, mobiles (kg/(cap year)) and **d** losses to soil and aquatic systems (kg/(cap year))



Consumption loss

Figure 5 shows that the action of the scenarios is different: An increase in separation efficiency immediately reduces this flow. This is because about 98% of the consumption loss is disposal to landfill, which is controlled by the recycling rate. Note that the increase after 2025 for this scenario is due to the fact that after 2025 the separation efficiency is constant at 0.9 but the output flows from consumption still increase (Fig. 4). An increase in lifetime or a copper ban reduces the consumption loss only after a time delay. Indeed the full effect is reached after a delay in the order of a lifetime. Additional forced dismantling first increases the consumption loss, since the output flows of consumption increase before they decrease due to reduced stocks. The stock of landfill in Fig. 5 is directly related to the consumption loss.

Loss to soil + aquatic systems

These flows are only reduced by the 'copper ban' and 'copper ban + forced dismantling' scenarios as shown in Fig. 5. Again, the full effect is reached only after a time delay in the order of a lifetime.

This discussion shows the following: It is easy to identify the key drivers to reduce flows such as consumption loss, loss to soil + aquatic systems or import flows. However, a dynamic model is crucial for understanding, discussing and comparing their quantitative effect as a function of time on these flows. This is due to the consumption dynamics which relates the stocks and outputs to the whole history of the input flows. As a consequence, possible measures to reduce input flows affect emissions from the stocks and the output flows with (large) time delays. This is in contrast to stationary systems where input changes cause an immediate change in emissions and output flows.

Conclusions

Copper is the most important scarce element in buildings and infrastructures. It is, however, a good indicator of the whole building sector due to its diverse applications.

The data exploration may be different for the dominant materials in the building sector such as stone, sand and wood. But the system analysis is the same and the use of all these materials is 'stock-driven': a certain stock per building, infrastructure or mobile is needed in order to provide a certain service. During this service the materials are not consumed. This contrasts with 'input-driven' materials such as food, which are consumed while providing the service. For these reasons, the stock-driven approach presented in this study can be applied to other substances in building, infrastructure and mobiles.

The aim of such dynamic models is to gain a system understanding on a long time scale rather than to produce very accurate numbers for flows and stocks. For systems with consumption dynamics characterised by long lifetimes, the output flows and stocks depend on the whole history of the input flows and vice versa. Only dynamic models can give an insight into the behaviour and interdependencies of these flows and stocks as a function of time, and into the differences in the effects of measures designed to reduce inputs, outputs or stocks.

The focus for copper is to reach a low consumption loss, since (a) copper stocks in the earth's crust are limited (b) copper mining induces a high environmental impact, and (c) copper accumulation in the environment represents a risk for living organisms.

The current use and consumption loss of copper in Switzerland are at high levels of 8 kg/(cap year) and 2 kg/(cap year), respectively. A further increase in recycling could reduce the losses to landfill. However, the analysis showed that even with 90% recycling the losses would still be 1 kg/(cap year). Moreover, the diffuse losses to the environment are not affected by increasing the recycling rate. They can only be reduced by substituting copper for other materials, i.e. by reducing the consumption stock. However, because of the long lifetimes involved, such measures have a delayed effect on the diffuse losses.

A discussion about reasonable measures and possible development must consider the whole system. This 'complete view' contrasts with the 'point-wise view' where each stakeholder focusses only on the part of his main interest. For instance a copper trader is mainly interested in high input flows whereas the environmental protection agency tries to minimise consumption losses to prevent damage to the environment. Such simulations can explain to stakeholders why and when flows and stocks increase or decrease and how measures could be optimised to control them in a desired way.

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Appendix A1: Model equations for buildings

For the explanation of the equations below, see "Mathematical model" section.

Buildings

Balance equation for stocks:

$$\dot{M}^{(3)}(t) = A_{13}(t) + A_{23}(t) - A_{36}(t) - A_{37}(t) \quad (3)$$

Abrasions/corrosion:

$$A_{37}(t) = a_{Build}(t) \cdot M^{(3)}(t) \quad (4)$$

Input into buildings:

$$A_{13}(t) + A_{23}(t) = I_{\mathrm{Inner}}(t) + I_{\mathrm{Outer}}(t) \quad (5)$$

Copper stock in buildings:

$$M^{(3)}(t) = M_{\mathrm{Inner}}(t) + M_{\mathrm{Outer}}(t) \quad (6)$$

Copper import into buildings:

$$A_{13}(t) = k_{\mathrm{ImpBuild}} \cdot (A_{13}(t) + A_{23}(t)) \quad (7)$$

$a_{\mathrm{Build}}(t)$ is a parameter function describing the specific abrasion and corrosion rate per stock unit per year. $k_{\mathrm{ImpBuild}}(t)$ is the fraction of copper imported into buildings.

Envelope of buildings

Balance equation:

$$\dot{M}_{\mathrm{Outer}}(t) = I_{\mathrm{Outer}}(t) - O_{\mathrm{Outer}}(t) \quad (8)$$

Copper stock:

$$M_{\mathrm{Outer}}(t) = P_{\mathrm{Outer}}(t) \quad (9)$$

Renewing:

$$O_{\mathrm{Outer}}(t) = \int_0^t k_{\mathrm{Outer}}(t,t') \cdot I_{\mathrm{Outer}}(t,t')\mathrm{d}t' \quad (10)$$

$P_{\mathrm{outer}}(t)$ is the copper stock in the OuterBuild. $k_{\mathrm{outer}}(t,t')$ is the transfer function or lifetime distribution of copper installed in the OuterBuild at a time t'.

Interior of buildings

For $M_{\mathrm{Inner}}(t)$, $I_{\mathrm{Inner}}(t)$ and $O_{\mathrm{Inner}}(t)$ similar equations to (8)–(10) apply.

Recycling:

$$A_{62}(t) = k_{\mathrm{Rec}}(t) \cdot (A_{62}(t) + A_{68}(t)) \quad (11)$$

$k_{\mathrm{Rec}}(t)$ is the fraction of recycling in the total output of dismantling/demolition.

Appendix A2: Calibration of the parameter functions

Stock for buildings P_{Inner}, P_{Outer}

Time series for the past of these stocks were compiled in Wittmer (2006) on the basis of the data sources mentioned above.

These time series show growth behaviour which is typical for all kinds of stocks. Logistic or sigmoidal curves are simple and turned out to describe growth adequately Fisher and Pry (1970). Logistic growth curves, and in particular linear-logistic and double logistic growth curves, were therefore fitted to these time series.

Logistic growth is exponential at the beginning, linear in the middle of the growth phase and decreasing towards the end until saturation is reached. Linear-logistic growth shows a linear pattern at the beginning of the growth period, followed by logistic growth. The derivation is continuous at the transition point.

This growth behaviour can be described mathematically as follows:

$$P_1(t) = \begin{cases} a_1(t - t_0) & t_0 \le t \le t_1 \\ p_{\text{init}} + \frac{p_{\text{sat}} - p_{\text{init}}}{1+e^{-\alpha(t-t_{\text{turn}})}} & t_1 \le t \end{cases} \tag{12}$$

t_0 is the initial point of the growth, a_1 the slope of the linear growth, p_{init} the initial value of the logistic part in the distant past $t \to -\infty$, p_{sat} the saturation value in the far future $t \to -\infty$, α is proportional to the maximum growth rate and t_{turn} is the turning point of the growth curve respectively.

The linear-logistic curve was chosen for buildings and mobiles because it proved to be more appropriate to the data than a simple logistic curve. An important parameter of the growth curves is the growth rate α, since typical values of this parameter are known for industrial or economics processes. The results of the non-linear fit for α are $\alpha_{\text{InnerBuild}} = 0.069$ and $\alpha_{\text{OuterBuild}} = 0.057$, respectively. These values are lower or comparable to typically observed growth rates for industrial products up to 0.15, see Bader et al. (2006). The results are presented in Fig. 6.

Lifetime distribution: k_{Inner}, k_{Outer}

The lifetime distribution can be described by a transfer function $k(t_{\text{Op}}, k_{\text{Ip}})$ in the two variables t_{Op} and t_{Ip} describing the amount of input at time t_{Ip} which leaves the balance volume at time t_{Op}.

The following two-parameter Gauss function was used as the lifetime distribution:

$$k(t, t') = \frac{1}{N_0} e^{-\frac{(t-t'-\tau(t'))^2}{2\cdot(\sigma(t'))^2}} \tag{13}$$

N_0: Normalisation factor; $\tau(t')$, $\sigma(t')$: average lifetime and widths of the lifetime distributions of copper inputs at input time t'. Note that τ and σ are the values of the maximum and width of the lifetime distribution rather than the average and standard deviation, respectively. This is because the lifetime distribution is a truncated normal distribution. For the usual cases where $\sigma \le \tau/2$, however, the difference between these quantities is small, namely, 2.9% for $\sigma = \tau/2$ and 0.1% for $\sigma = \tau/3$, etc. We therefore refer to τ and σ as the average and standard deviations of the lifetime distribution.

This lifetime distribution was discussed in detail in Baccini and Bader (1996) and applied in many case studies (Zeltner et al. 1999; Müller et al. 2004; Binder et al. 2001; Bader et al. 2006).

Estimates for τ and σ were obtained as follows. Since no time series data are available, we assume τ and σ to be a constant function of time in the sense of a first approximation.

Buildings: k_{Inner}, k_{Outer}: τ and σ are obtained from the experience of experts and tradesmen.

The estimated parameters τ and σ are listed in Table 4.

Abrasion/corrosion coefficients: a_{Build}

The abrasion/corrosion was assumed to be proportional to the surfaces exposed. For the infrastructures and buildings, the relevant surfaces of cables and sheets were related to the corresponding masses. The specific abrasion and corrosion rates were found in the literature [von Arx (1998): abrasion rate: 0.0036/year, Faller (2001): corrosion rate: 1.8 g/(m^2 year), He et al. (2001): corrosion rate for Sweden 1.3 g/(m^2 year)].

Appendix A3: Adaptation of the model to specific scenarios

Scenario: Copper ban in the envelope of buildings

The adaptation of the model is very simple: Eq. 9 for the copper stock of the building envelope has to be changed as follows:

Copper stock:

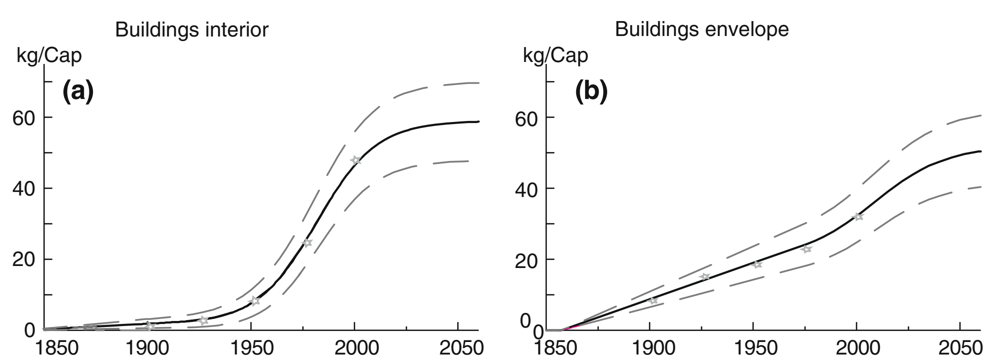

Fig. 6 Fitted growth curves and data sets for stocks of buildings

Table 4 Values and uncertainties for parameter functions that are a constant function of time

	Value	Standard deviation
a_{Build}: Corrosion buildings (1/year)	0.00025	0.000125
τ Building (year)	40	10
σ Building (year)	20	5

$$M_{\mathrm{Outer}}(t) = P_{\mathrm{Outer}}(t) \quad \text{for } t \leq t_{\mathrm{Ban}}^{(\mathrm{Outer})} \tag{9a}$$

$$I_{\mathrm{Outer}}(t) = 0 \quad \text{for } t > t_{\mathrm{Ban}}^{(\mathrm{Outer})}$$

$t_{\mathrm{Ban}}^{(\mathrm{Outer})}$ is the time at which the copper ban begins for the envelope of the buildings.

Scenario: Copper ban + copper dismantling in the envelope of buildings

In addition to the modification equation (9a) above, Eq. 10 must also be adapted.

Renewal and dismantling:

$$O_{\mathrm{Outer}}(t) = \int_0^t k_{\mathrm{Outer}}(t,t')I_{\mathrm{Outer}}(t,t')\mathrm{d}t' \quad \text{for } t \leq t_{\mathrm{Ban}}^{(\mathrm{Outer})} \tag{10a}$$

$$O_{\mathrm{Outer}}(t) = O_{\mathrm{Outer}}^{(\mathrm{Renew})}(t) + O_{\mathrm{Outer}}^{(\mathrm{Dism})}(t) \quad \text{for } t > t_{\mathrm{Ban}}^{(\mathrm{Outer})}$$

where

$$O_{\mathrm{Outer}}^{(\mathrm{Renew})}(t) = \int_{t_{\mathrm{Ou}}(t)}^{t} k_{\mathrm{Outer}}(t,t')I_{\mathrm{Outer}}(t')\mathrm{d}t' \tag{10b}$$

$$O_{\mathrm{Outer}}^{(\mathrm{Dism})}(t) = P_{\mathrm{Outer}}^{(\mathrm{Dism})}(t) \cdot M_{\mathrm{Outer}}(t) \tag{10c}$$

$O_{\mathrm{Outer}}^{(\mathrm{Renew})}(t)$ and $O_{\mathrm{Outer}}^{(\mathrm{Dism})}(t)$ are the copper outputs of *OuterBuild* due to renewing and dismantling, respectively. $P_{\mathrm{Outer}}^{(\mathrm{Dism})}(t)$ is the specific dismantling rate per stock unit per year. $t_{\mathrm{Ou}}(t)$ is the age (relative to the initial time 0) of the oldest copper in *OuterBuild* that has not yet been removed due to renewing and dismantling. For $t_{\mathrm{Ou}}(t)$, the following ordinary differential equation applies:

$$\frac{\mathrm{d}t_{\mathrm{Ou}}}{\mathrm{d}t} = \frac{O_{\mathrm{Outer}}^{(\mathrm{Dism})}(t)}{I_{\mathrm{Rest}}(t, t_{\mathrm{Ou}}(t))} \tag{10d}$$

where

$$I_{\mathrm{Rest}}(t,t') = I_{\mathrm{Outer}}(t')\left[1 - \int_{t'}^{t} k_{\mathrm{Outer}}(t'',t')\mathrm{d}t''\right]$$

is the rest of the copper output into *OuterBuild* at a time t' and not renewed until a time t.

Equations (10a) are a generalisation of the relevant equations in Müller et al. (2004) and Bader et al. (2006). For reasons of simplicity in Eq. 10a, it was assumed that the copper ban and forced dismantling have the same onset time.

However, this is not a restricting assumption. Note that Eq. 10c is a possible but reasonable approach to the dismantling flow $O_{\mathrm{Outer}}^{(\mathrm{Dism})}$, representing a dismantling process that is proportional to the stock.

References

Baccini P, Bader HP (1996) Regionaler Stoffhaushalt. Spektrum Akad.Verlag, Heidelberg

Baccini P, Brunner P (1991) Metabolism of the anthroposphere. Springer-Verlag, Berlin

Baccini P, Daxbeck H, Glenck E, Henseler G (1993) Metapolis Güterumsatz und Stoffwechselprozesse in den Privathaushalten einer Stadt. NFP „Stadt und Verkehr", Zürich. Forschungsberichte; 34A

Bader HP, Real M, Scheidegger R (2003) Large scale implementation of Solar Home Systems in remote, rural areas. Clean Technol Environ Policy 6:18–25

Bader HP, Scheidegger R, Real M (2006) Global renewable energies: a dynamic study of implementation time, greenhouse gas emissions and financial needs. Clean Technol Environ Policy 8:159–173

Bergbäck B (1992) Industrial metabolism. The emerging immission landscape of heavy metal immission in Sweden. Dissertation, Linköping Studies in Arts and Science, no. 76

Bergbäck B, Anderberg S, Lohm U (1994) Accumulated environmental impact: the case of cadmium in Sweden. Sci Total Environ 145:13–28

Bergbäck B, Johansson K, Mohlander U (2001) Urban metal flows—a case study of Stockholm: review and conclusions. Water Air Soil Pollut 1(3–4):3–24

Binder C, Bader HP, Scheidegger R, Baccini P (2001) Dynamic models for managing durables using a stratified approach: the case of Tunja, Columbia. Ecol Econ 38:191–207

Brun R, Reichert P, Künsch HR (2001) Practical identifiability of large environmental simulation models. Water Resour Res 37(4):1015–1030

Chèvre N, Guignard C, Rossi L, Pfeifer HR, Bader HP, Scheidegger R (2010) Substance flow analysis as a tool for urban water management: the case of copper in Lausanne, Switzerland. Water Sci Technol (accepted)

Daigo I, Hashimoto S, Matsuno Y, Adachi Y (2009) Material stocks and flows accounting for copper and copper-based alloys in Japan. Resour Conserv Recycl 53(4):208–217

Erdmann L, Handke V, Klinski S, Behrendt S, Scharp M (2002) Nachhaltige Bestandsbewirtschaftung nicht erneuerbarer knapper Ressourcen Handlungsoptionen und Steuerungsinstrumente am Beispiel von Kupfer und Blei ITZ: Institut für Zukunftsstudien und Technologiebewertung Berlin

Faller M (2001) Metallabtrag und Metallabschwemmung von Metalldächern: Untersuchungsergebnisse der Freibewittersversuche in der Schweiz. BAUMETALL 4:52–59

Fisher JC, Pry RH (1970) Simple substitution model of technological change. General Electric Company's Research and Development Center report 70-C-215, Schenectady, NY

He W, Wallinder IO, Leygraf CA (2001) Comparison between corrosion rates and runoff rates from new and aged copper and zinc as roofing material. Water Air Soil Pollut 1(3–4):67–82

Hedbrant J (2003) Structuring empirical knowledge on environmental issues. Dissertation, Linköping Studies in Arts and Science, no. 283

Hug F, Bader HP, Scheidegger R, Baccini P (2004) A dynamic model to illustrate the development of an interregional energy household to a sustainable status. Clean Technol Environ Policy 6:138–148

Iverfeldt A (ed) (2001) Metals in the urban and forest environment. Water Air Soil Poll Focus 1(3–4):1–476

Johnstone IM (2001a) Energy and mass flow of housing: a model and example. Build Environ 36:27–41

Johnstone IM (2001b) Energy and mass flows of housing: estimating mortality. Build Environ 36:43–51

Jolly JWL, Edelstein DL (1989) Copper in: minerals yearbook. US Department of Commerce, Bureau of Mines, Washington, pp 339–386

Jordi B (2004) Recycling - die Rohstoffquelle der Zukunft. BUWAL UMWELT 1/04, Bern, pp 35–38

Kohler N, Hassler U, Paschen H (1999) Stoffströme und Kosten in den Bereichen Bauen und Wohnen. Springer Verlag, Berlin

Lichtensteiger T (Hrsg) (2006) Bauwerke als Ressourcennutzer und Ressourcenspender in der langfristigen Entwicklung urbaner Systeme. vdf Hochschulverlag AG an der ETH Zürich

Lohm U, Bergbäck B, Hedbrandt J, Jonsson A, Svidén J, Sörme L, Östlund C (1997) Databasen. Stockholm. Flöden och ackumulation av metaller i Stockholms teknosfär. Linköping University, Tema Vatten Rapport 25

Metallgesellschaft AG (1992) Metallstatistik 1982-1992, vol 80 (also vols 70, 60, 50, 30, 10). Metallgesellschaft AG, Frankfurt am Main

Müller D, Bader HP, Baccini P (2004) Physical characterization of regional timber management for a long-term scale. J Ind Ecol 8(3):65–88

Nilarp F (1994) Omsättningen av koppar i Sverige i ett bärkraftighetsperspektiv. Chalmers University of Technology and Gothenburg University, Department of Physical Resource Theory

Pfister F, Bader HP, Scheidegger R, Baccini P (2005) Dynamic modelling of resource management for farming systems. Agric Syst 86(1):1–28

Schaffner M, Bader H-P, Scheidegger R (2009) Modelling the contribution of point sources and non point sources pollution to Thachin River. Sci Total Environ 407:4902–4915

Schmid Neset T, Bader HP, Scheidegger R (2006) Food consumption, nutrient flows: nitrogen in Sweden since the 1870 s. J Ind Ecol 10(4):61–75

Schmid Neset T, Bader HP, Scheidegger R, Lohm U (2008) The flow of phosphorus in food production and consumption Linköping, Sweden, 1870-2000. Sci Total Environ 396(2–3):111–120

Sigg L, Behra R, Boller M, Eggen R, Meier W, Sulzberger B, Xue HB (1999) Relevance of copper inputs in natural waters. EAWAG News 46E:9–11

Sörme L (2003) Urban heavy metals stocks and flows. Dissertation, Linköping Studies in Arts and Science, no. 270

Sörme L, Lagerkvist R (2002) Sources of heavy metals in urban wastewater in Stockholm. Sci Total Environ 298:131–145

Spatari S, Bertram M, Fuge D, Fuse K, Graedel H, Rechberger TE (2002) The contemporary European copper cycle: 1 year stocks and flows. Ecol Econ 42(1–2):27–42

Spatari S, Bertram M, Gordon RB, Henderson K, Graedel TE (2005) Twentieth century copper stocks and flows in North America: a dynamic analysis. Ecol Econ 54(1):37–51

Tarr J, Ayres R (1990) The earth as transformed by human action: global and regional changes in the biosphere over the past 300 years. In: Turner BL et al (eds) The Hudson-Raritan River basin, 1790–1980. Cambridge University Press, New York, pp 623–640

van der Voet E, Guinée Jeroen B, de Haes U, Helias A (eds) (2000) Heavy metals: a problem solved? Methods and models to evaluate policy strategies for heavy metals series: environment & policy, vol 22. Kluwer Academic Press, London

Von Arx U (1998) Kupfer in der Schweiz (Standortbestimmung). BUWAL, Bern

Wang T, Mao J, Johnson J, Rack RK, Graedel TE (2008) Anthropogenic metal cycles in China. J Mater Cycles Waste Manage 10:188–197

Wittmer D (2006) Kupfer im regionalen Ressourcenhaushalt – Ein methodischer Beitrag zur Exploration urbaner Lagerstätten. Dissertation ETH Zürich, vdf Hochschulverlag AG ETH Zürich; 16325

Wittmer D, Lichtensteiger Th, Baccini P (2003) Copper exploration for urban mining. In: Lagos GE, Warner AEM, Sanchez M (eds) Proceedings of Copper 2003. Health, environment and sustainable development, vol 11, pp 85–101

Xue HB, Oestreich A, Kistler D, Sigg L (1996) Free cupric ion concentrations and Cu complexation in selected Swiss lakes and rivers. Aquat Sci 58(1):69–87

Zeltner C, Bader H-P, Scheidegger R, Baccini P (1999) Sustainable metal management exemplified by copper in the USA. Reg Environ Changes 1:31–46